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THE BRADLEY DEPARTMENT OF ELECTRICAL ENGINEERING

VIRGINIA TECH

"FEASIBILITY STUDY OF A SYNTHESIS PROCEDURE FOR ARRAY FEEDS TO IMPROVE RADIATION PERFORMANCE OF LARGE DISTORTED REFLECTOR ANTENNAS"

by

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FEASIBILITY STUDY OF A SYNTHESIS PROCEDURE FOR ARRAY FEEDS TO IMPROVE RADIATION PERFORMANCE OF LARGE DISTORTED REFLECTOR ANTENNAS

FINAL REPORT

submitted to

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for

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by

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1. INTRODUCTION

Virginia Tech began a seven year relationship with NASA Langley in 1987 with the goal of investigating large reflector antennas in space. This effort is complete and this report serves as a final report. The report will summarize the findings with focus on significant contributions. There was a considerable amount of documentation that flowed from the effort. The journal articles, presentations at professional meetings, and technical reports are listed in Chapter 3.

The projects that compose the program are listed in Table 1-1 together with the duration and funding. Consistent with the nature of a grant, research direction was set by mutual agreement between LaRC and VPI & SU based on the needs of NASA and logical technical goals. This worked well and short term goals as well as fundamental investigations could both be pursued.

Perhaps the most important product of the effort is the students whose research was supported through this program. The students with the degrees they received and current employment are listed in Table 1-2. Of course, the benefit to U.S. engineering from these graduates will be long lasting. The direct involvement of the students in the solution of real engineering problems was key to their development.

Table 1-1

Summary Grant Awards for the Program

1. "A Comparison of Physical Optics and Geometrical Optics Methods for Computation of Reflector Surface Error Effects"
   NASA Grant: 3126501
   Term: June 15 - December 31, 1987
   Funding: $22,270

2. "Feasibility Study of a Synthesis Procedure for Array Feeds to Improve Radiation Performance of Large Distorted Reflectors"
   NASA Grant: NAG-1-859
   Term: February 25, 1988 - December 31, 1993
   Funding: $415,995

Table 1-2

Students Associated with the NASA/Langley - Virginia Tech Reflector Antenna Research Program

Student	Degree	Year	Current Employment
W.T. Smith	Ph.D.	1990	U. of Kentucky faculty
P. Werntz	Ph.D.	1993	Booz-Allen & Hamilton, Inc., Arlington, VA
J. LaPean	M.S.	1993	Ph.D. student at Virginia Tech
B. Shen	Ph.D.	1993	Tarus Products, Detroit, MI
K. Takamizawa	Ph.D.	Expected 1994	Finishing dissertation at Virginia Tech

2. SUMMARY OF FINDINGS DURING THE COURSE OF THE PROGRAM

2.1 Overview

There were several tangible products that resulted from the reflector antenna research program. Table 2-1 summarizes them. As mentioned in Chapter 1 the five advanced degreed students are perhaps the most important product.

The initial technical effort was to develop techniques to compensate for distortions over the surface of the main reflector of a large reflector antenna system. An in-depth investigation of this problem resulted in a new technique for the electronic correction of surface errors. A journal article [3.1-4] on the findings describe the use of the iterative sampling method.

Shortly after the "Mission to Planet Earth" program started we began investigating the use of large reflector antennas in geostationary orbit for passive earth remote sensing. A study panel was coordinated by Virginia Tech [3.3-4] to set technical goals for the effort. These were used to guide the design of several antennas which are described in the next section.

The reflector antenna research program at Virginia Tech is summarized in Fig. 2-1. The original interest stemmed from an industrial (Reynolds Metals) need and currently involves work with industry (Prodelin Corp.) on high technology, low cost reflectors. The intervening years (1987 - 1993) is the period of this report and Virginia Tech's reflector antenna activity then was exclusively with NASA LaRC.

2.2 Three Antenna Designs

Peter Foldes of Foldes, Inc., proposed several designs for reflector antenna systems to meet the goals of the program. The primary constraints were to have a 25-m main reflector which can scan $\pm 5^{\circ}$ with limited mechanical motion. The Foldes concepts were based on geometrical optics design rules.

After several technical interchanges between Foldes, Langley, and Virginia Tech, two designs were selected for detailed investigation. These were reflectors called Type 1 (formerly Foldes Type 6) and Type 2 (formerly Foldes Type 2). Type 1 is a dual reflector with a moving

Table 2-1

Summary of Significant Findings and Products in the NASA LaRC - Virginia Tech Reflector Antenna Research Program

- Five advanced degrees
- Developed techniques to compensate for surface error distortions in mesh reflector using array feeds.
- Purchased the world standard reflector antenna computer code (GRASP7) including a site license for use at NASA Langley and Virginia Tech.
- Three complete designs for large reflector antennas with scan capability while not moving the main reflector or feed antenna. One of these (the spherical tri-reflector with a flat mirror) is currently in the patent process.

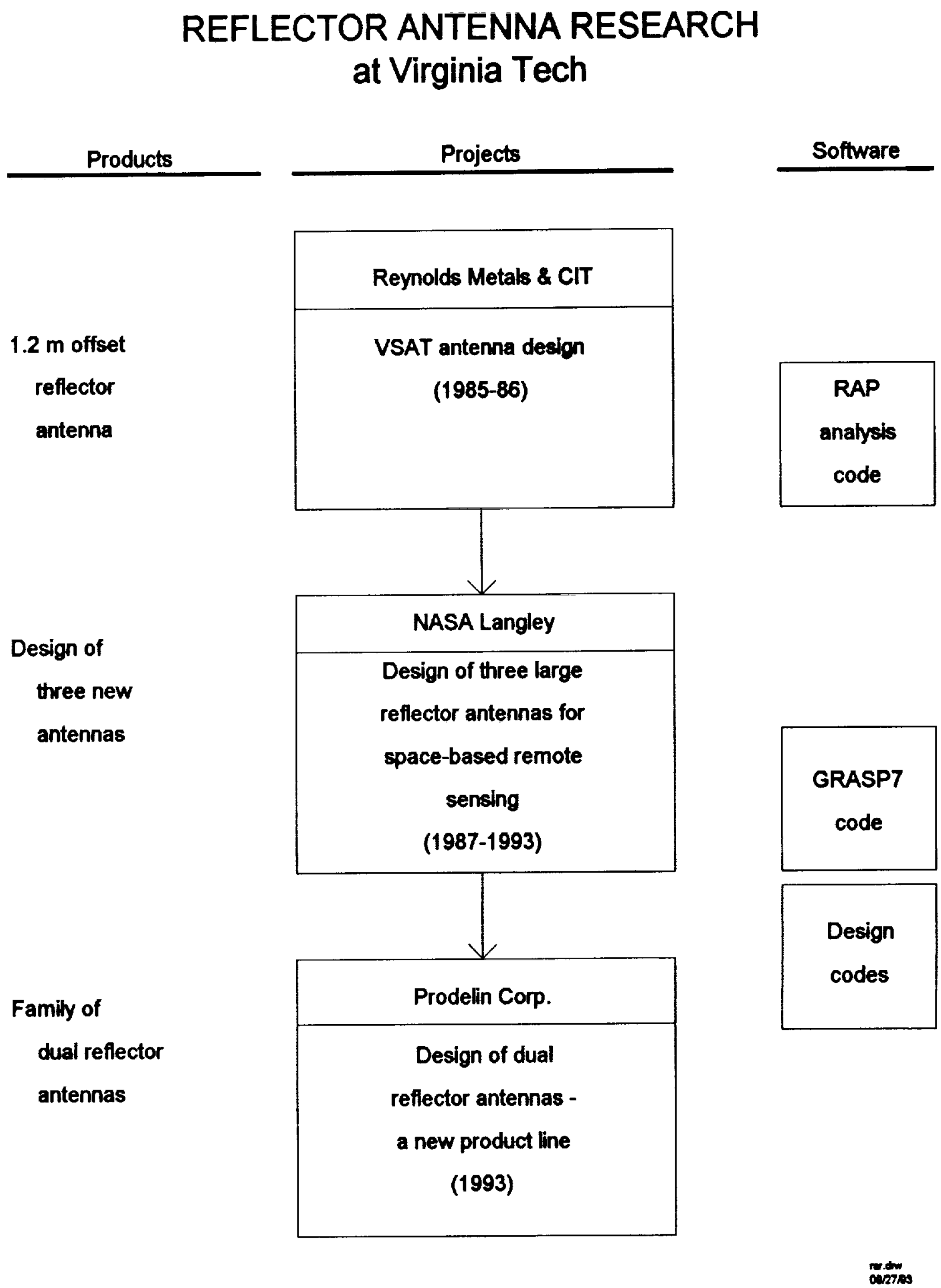

Figure 2-1. A block diagram of reflector antenna reserach at Virginia Tech.

subreflector and Type 2 is a tri-reflector with a moving tertiary. Both were analyzed and evolved through a performance maximization design step based on geometrical optics and a final performance evaluation with physical optics using the GRASP7 code. We added a third design which is a spherical main reflector with two subreflectors and a moving flat mirror. Details of all these designs are documented in the references of Chap. 3 including a journal article on two of them [3.1-5, 3.1-6]; three more articles are in preparation.

Table 2-2 summarizes the performance of three designs. The goals were achieved. First, performance estimates by Peter Foldes were exceeded. That is, scan range was larger than predicted for Types 1 and 2. Second, as expected, performance increases with system complexity. Finally, a full range of performance is available with these three designs.

Perhaps the "best" configuration is the spherical reflector. It can scan over wide ranges with no performance degradation. This antenna system is now being patented.

2.3 Beam Scan Optimization Techniques

The majority of reflector antennas are designed to produce a single on-axis beam. Such reflector systems are called single focal point reflector systems. The scanning of the beam in a single focal point reflector system can be accomplished by displacing the feed antenna away from the focal point of the reflector antenna. Equivalently, the image of feed antenna can be displaced with the motion of one or more of subreflectors in a multiple reflector antenna system. Both Type 1 and Type 2 configurations as described in the previous section are single focal point reflector antennas where scanning is accomplished by the displacement of feed image. Beam scanning using single reflector antennas have the best radiation pattern performance when the beam is in the on-axis direction and have gradual degradation as the beam is scanned off axis.

Using a dual reflector antenna configuration it is also possible to design a system with two exact focal points. Such reflector antenna systems have their best radiation characteristics in two beam directions corresponding to the two focal points, and beam degradation away from these focused directions is gradual. A bifocal reflector system can be utilized for improved scan

Table 2-2

Characteristics of Five Wide Scanning Reflector Antenna System

Parameter	Prime-focus Parab. Feed movement		Type 1 (LaPean)	Type 2 (Werntz)	Spherical (Shen)
	Lateral	Petzval			
Main reflector diameter $(D_M), \lambda$	--------	700	2835	480	1200x1000
F/D_p	1.0000	1.0000	0.515	0.519	0.260
Areal efficiency $\left(\frac{D_{M^2}}{D_{M^2}+\ldots+D_{Sn^2}}\right)$	1.0000	1.0000	0.9817	0.8818	0.9218
Translational degrees of freedom	1	2	3	0	0
Rotational degrees of freedom	1	1	2	2	feed: 1 mirror: 2
Gain (G), dBi	--------	--------	77.78	62.44	63
Aperture efficiency (ε_{ap}), %	--------	--------	75.63	77.13	50
1 dB gain loss scan range, HPBW	8	34x0	50	30x60	82

characteristics for planar scan where two focal points are located at the limits of the scan plane. However, bifocal systems cannot be used to improve radiation characteristics for two dimensional scanning, such as in both the θ and ϕ planes.

The beam scan optimization technique under investigation improves the radiation pattern characteristics of reflector antennas within a desired beam scan region that can be either a plane or a cone. The basic idea behind the technique is to modify shapes of reflector surfaces of a single focal point reflector antenna such that the radiation characteristics in the outer limits of scan coverage are improved while some degradation in the radiation characteristics in the on axis beam is allowed. Ideally, the changes in the reflectors are designed such that they induce small but uniform radiation pattern degradation within the desired scan region.

During the last four years of effort several fundamental scanning issues using reflector antennas were addressed as well as the scan optimization technique. Progress was made in answering some of the questions but much remains. The following summarizes the key results in scan optimization technique study. A complete report on the effort will be provided in the future.

2.3.1 Definition of scan optimization

In general, it is possible to improve either efficiency or scan coverage by modifying the surfaces of reflector antennas. These two characteristic groups must be traded off; if one is improved, the other degrades. The efficiencies that can be improved include aperture, beam, spillover, and surface utilization efficiencies. The parameters that define the radiation pattern characteristics such as gain, side lobe level, and cross polarization level are also part of the efficiency group. The optimization in this group is established by satisfying the proper feed pattern-to-aperture field mapping. It has been shown that scan capabilities of high gain dual shaped reflectors which satisfy the mapping are less than that of conventional Cassegrain reflectors.

The reflector antenna surface shapes can be also altered from the single focal point systems to improve the radiation patterns within the scan range. Some of the examples of improved scan reflectors are spherical, bifocal, and Schwarzschild systems. The spherical tri-reflector systems studied by Shen, Watanabe, and Kildal are ideal scanning reflector systems that suffer very little beam degradation within the limits of scan region. However, all of the configurations require some degree of oversizing of the spherical primary reflector which reduces the reflector utilization efficiency and aperture efficiency.

The scan optimization technique studied yields the reflector configurations that are a compromise between the maximum efficiency and maximum scan capability.

2.3.2 Description of optimization technique

The reflector configurations are described by their positions, orientations and surface shapes. To solve for a scan optimized reflector configuration an error function representing the required efficiency as well as the required scan capabilities must be determined. The solutions are obtained by minimization of the error function which can be solved using one of the available numerical techniques.

The error function can be determined either in the far field or in the aperture plane. There are also several choices of analysis techniques to determine the reflector fields. This study used the aperture fields which are determined by geometrical optics (Sections 2.3.5 and 2.3.6) and the far fields which are determined by physical optics (Section 2.3.7). Modified Powell's method was used to minimize the error function [Numerical Recipes].

2.3.3 Reflector positions and orientations

The scanning is accomplished by translational and rotational displacement of one of the subreflectors (secondary reflector for Type 1, tertiary reflector for Type 2). There are three degrees of freedom in the translational displacements in x, y, and z directions, and three degrees of freedom in the rotational displacements in α, β, and γ angles. The original (unoptimized) Type 1 and Type 2 configurations allowed only two degrees of rotational displacements in α and

β. The results for Type 1 configurations show a significant improvement in scanning by introducing the third rotational variable. However, this additional rotational displacement may be difficult to implement without a substantial increase in the mechanical complexity and weight.

2.3.4 Reflector surface shapes

Scan optimization is accomplished by altering the shape of reflector surfaces. The reflector surfaces are expressed in terms of two subfunctions:

$$f = f_o + f_d$$

where f_o represents the initial shape of the reflector surface and f_d represents the change in the reflector shape. Usually, f_o is represented in analytical form for single focal point reflectors. The change in the surface shape f_d often cannot be solved analytically, and thus it must be represented in series form. In addition, the radius of the curvature of the surface function f_o is generally larger than that of f_d prohibiting the use of the same series to represent both f_o and f_d.

A modified form of truncated Zernike polynomial defined over a unit circle was used in this study to represent f_d. Zernike polynomials were used because they are directly related to the primary aberration that exist in the aperture fields when beam is scanned.

2.3.5 Results - Type 1

The efforts were conducted with assumptions that the primary reflector as well as the feed assembly are stationary. In addition, no increase of the diameter of primary reflector was allowed in order to achieve close to 100 percent reflector surface utilization efficiency. These assumptions are the same as ones used for the original Type 1 studies. The diameter of the secondary reflector, on the other hand, was allowed to increase from the original Type 1 configuration. In fact, the increase of at least one of the reflector diameters in the dual reflector configuration is necessary to apply scan optimization.

The error function was computed from aperture field distribution using geometrical optics for 9 scan positions $(\theta,\phi) = (0°,0°)$, $(\theta_0,0°)$, $(\theta_0,\pm 45°)$, $(\theta_0,\pm 90°)$, $(\theta_0,\pm 135°)$, and $(\theta_0,180°)$

where θ_0 is the desired limit of scan in θ plane. Improvements in scan range were accomplished as reported in the October 1993 semiannual status report.

2.3.6 Results - Type 2

The scan optimization technique was applied on the primary and the tertiary reflector surface shapes. The shape of the secondary reflector was not modified to keep the conjugate points at the center of primary and tertiary reflectors. The improvements obtained by the scan optimization were very small. Further studies are necessary to optimize the scan capabilities of Type 2 configuration.

2.3.7 Use of higher order analysis techniques

The use of higher order analysis techniques for computation of error functional was investigated. To simplify the computational constraint the study was conducted for two-dimensional infinite cylindrical reflector systems. The error function was derived from the far field radiation pattern obtained from the electromagnetic field analysis using physical optics. The results for Type 1 configuration using the physical optics scan optimization show very little improvement over the results obtained with geometrical optics scan optimization. This technique may be useful to improve the scan capabilities of reflector antennas with relatively small electrical aperture size where discrepancies between geometrical optics and higher order analyses are large.

3. LIST OF PUBLICATIONS

3.1 Journal Articles

(1) W.L. Stutzman, S.W. Gilmore, and S.H. Stewart, "Numerical evaluation of radiation integrals for reflector antenna analysis including anew measure of accuracy," IEEE Trans. on Ant. and Prop., vol. AP-36, pp. 1018-1023, July 1988.

(2) W.T. Smith and W.L. Stutzman, "A pattern synthesis technique to compensate for distortions in large reflector antennas," IEEE Ant. and Prop. Society International Symposium Digest (Dallas), pp. 1872-1875, May 1990.

(3) S.H. Stewart and W.L. Stutzman, "Analysis of reflector antenna systems with arbitrary feed arrays using primary field superposition, IEEE Trans. on Ant. and Prop., vol. 38, No. 7, pp. 994-1000, July 1990.

(4) W.T. Smith and W.L. Stutzman, "A pattern synthesis technique for array feeds to improve radiation performance of large distorted reflector antennas," IEEE Trans. on Ant. and Prop., vol. 40, pp. 57-62, Jan. 1992.

(5) Bing Shen and Warren L. Stutzman, "Design of scanning spherical trireflector antennas with high aperture efficiency," IEEE Trans. on Ant. and Prop., vol. 41, No. 6, pp. 778-786, June 1993.

(6) P.C. Werntz, W.L. Stutzman, K. Takamizawa, "A high gain tri-reflector antenna configuration for beam scanning," IEEE Trans. on Ant. and Prop., to appear.

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(2) W.T. Smith and W.L. Stutzman, "A comparison of physical optics and geometrical optics for computation of reflector surface error effects," Proc. of IEEE Southeastcon (Columbia, SC), pp. 214-219, April 1989.

(3) W.L. Stutzman and W.T. Smith, "Feasibility study of a synthesis procedure for array feeds to improve radiation performance of large distorted reflector antennas," URSI National Radio Science Meeting (Boulder, CO), Jan. 3-5, 1990.

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(6) P.C. Werntz, M.C. Bailey, K. Takamizawa, and W.L. Stutzman, "An array fed tri-reflector system for wide angle beam scanning," IEEE Ant. and Prop. Society International Symposium Digest (Chicago), pp. 8-11, July 1992.

(7) Koichiro Takamizawa, Paul C. Werntz, and Warren L. Stutzman, "Optimization of multiple reflector antenna configurations for wide angle scan," IEEE Ant. and Prop. Society International Symposium Digest (Chicago), pp. 359-362, July 1993.

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(9) Bing Shen and Warren L. Stutzman, "Methods to improve the aperture efficiency and simplify the mechanical motion of spherical main reflector scanning antennas," URSI National Radio Science Meeting (Boulder, CO), Jan. 1993.

(10) Bing Shen and Warren L. Stutzman, "Beam efficiency evaluation of large reflector radiometer antennas," URSI National Radio Science Meeting (Boulder, CO), Jan. 1993.

3.3 Reports

(1) W.T. Smith and W.L. Stutzman, "A comparison of physical optics and geometrical optics methods for computation of reflector surface error effects," Virginia Tech Satellite Communications Group Report EE SATCOM 87-2 to NASA Langley under contract NAS1-18471-Task 1, 130 pp., Dec. 1987.

(2) W.L. Stutzman and W.T. Smith, "Feasibility study of a synthesis procedure for array feeds to improve radiation performance of large distorted reflector antennas," Final Report, Grant No. NAG-1-859, Virginia Tech Report No. EE SATCOM 90-2, 247 pp., Aug. 1990.

(3) W.L. Stutzman, K. Takamizawa, P. Werntz, J. LaPean, R. Barts, and B. Shen, "Feasibility study of a synthesis procedure for array feeds to improve radiation performance of large distorted reflector antennas," Semiannual Status Report to NASA Langley Research Center under Grant No. NAG-1-859, Virginia Tech Report No. EE SATCOM 91-5, 45 pp., Aug. 1991.

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(8) Paul C. Werntz, "A high gain tri-reflector antenna configuration for beam scanning," Ph.D. Dissertation, Virginia Tech Report No. EE SATCOM 93-7, 321 pp., May 1993.

(9) Bing Shen, "Multiple reflector scanning antennas," Ph.D. Dissertation, Virginia Tech Report No. EE SATCOM 93-14, 101 pp., July 1993.

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